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Economic Benefits of Modern Exothermic Feeders in Foundry Processes

Master's thesis for the degree of Master of Science in Technology submitted for inspection.

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Abstract of master's thesis

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Abstract

The labour costs in countries like Finland are relatively high. To gain competitiveness against countries with low-cost labour, cost efficient manufacturing methods must be favoured. This thesis is a case study of the holistic cost impact of modern exothermic feeders in foundry processes. These feeders are small, flexible regarding application and have features that can improve casting quality. It is, however, not studied how these beneficial factors affect the costs throughout the foundry's manufacturing processes.

In this thesis, the following foundry processes are examined: (1) mould preparation, (2) melt shop and casting, (3) blasting and (4) fettling and heat treatment. Parameters that are affected by the change of feeder type are measured for three castings in two different foundries in Finland. Ultimately, a holistic view of the cost impact of modern exothermic feeders is presented.

The results achieved with three diverse castings depended heavily on the characteristics of the castings. Change from isolating feeders gave bigger savings than change between conventional and modern exothermic feeders. Moreover, the number and size of feeders affected the achieved savings. The biggest saving of 14% was achieved with a test casting having four isolating feeders to start with. The second casting had smaller feeder volume and fewer feeders. As a result, the savings were reduced to 11%. The only casting with conventional exothermic feeders to start with did not show any cost savings. Its costs were increased by 31%, mostly due to higher feeder cost.

The castings of the study were all rather simple regarding the feeder positioning. This did not allow the full potential of modern exothermic feeders to be revealed. However, the results can already give tools for foundries to understand how the use of modern exothermic feeders can affect the costs overall.

Keywords feeding, casting, exothermic feeders, foundry processes, economic benefits

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Sammandrag av diplomarbetet

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Sammandrag

Kostnaderna för arbetskraft i länder som Finland är relativt höga. För att vara konkurrenskraftiga gentemot länder med billig arbetskraft måste man använda sig av kostnadseffektiva produktionssätt. Detta diplomarbete är ett fallstudie över kostnadsinverkan av moderna exotermiska matare för gjuteriprocesser. Dessa matare är mindre till sin storlek, är mer flexibla gällande deras användningssätt och har egenskaper som kan gynna kvaliteten av gjutstycken. Det har dock inte forskats hur dessa nyttiga egenskaper påverkar kostnaderna i sin helhet för olika tillverkningsprocesser i gjuterier.

Gjuteriprocesserna betraktade i detta diplomarbete är: (1) formberedning, (2) smälteriet och gjutning, (3) blästring och (4) putsning och värmebehandling. Parametrar som påverkas av byte av matare är mätta för tre gjutstycken i två olika gjuterier i Finland. Till slut presenteras en holistisk syn på kostnadsinverkan av moderna exoterma matare.

Resultaten för gjutstycken var mycket beroende av gjutstyckenas egenskaper. Byte från isolerande matare gav större besparingar än byte från konventionella exotermiska matare. Också mängden matare och matarstorlek påverkar hur stora besparingar kan nås. Största besparingen av 14% uppnåddes med ett gjutstycke som hade fyra isolerande matare till att börja med. Andra testgjutstycket hade mindre matarvolym och färre matare så besparingarna minskade till 11%. Det enda gjutstycket med konventionella exotermiska matare från att börja med visade inte några besparingar. Dess kostnader ökade med 31%, mestadels på grund av förhöjda matarkostnader.

De inspekterade gjutstycken var alla relativt enkla gällande läget av mataren. Detta gjorde att fulla potentialen av moderna exotermiska matare inte kunde uppdagas. Oberoende detta kan resultaten redan användas av gjuterier för att förstå hur användandet av moderna exotermiska matare kan påverka kostnaderna överlag.

Nyckelord matning, gjutning, exotermiska matare, gjuteriprocesser, ekonomiska nyttor

Preface

As I have gained insight to technical sales, I have understood the importance of practical experiences. If you cannot present them, it is tough to penetrate the barriers of status quo and established ways of working. Moreover, purchase departments are seldom able to perceive holistic cost impacts, thus restraining the use of cost-efficient productive goods.

This thesis is written for Oy Lux Ab with the goal to gain insights in these holistic cost impacts in practice. Oy Lux Ab acted as sponsor and provided the test feeders for the case studies. The collaborating foundries granted me permission to test the feeders on their production castings.

I want to thank Oy Lux Ab for making it possible to write this thesis alongside my other duties. I am also thankful for the collaborating foundries and the time the personnel have spent on making these tests possible. Finally, I want to thank my supervisor, Professor Juhani Orkas, and my advisor, Hannu Karjalainen for allocating their valuable time to guide me through this process.

Espoo 30.7.2020

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Table of contents

1 Introduction

The manufacturing industry in Finland has for the previous decades been struggling with its competitiveness compared to countries with cheaper labour. One solution has been to increase the productivity and reduce the need of manual labour (Santacecilia 1992, Schmidt 2013). This thesis is studying whether modern exothermic feeders can be used to achieve cost savings in foundry processes.

Casting as a manufacturing method has unique properties that no other manufacturing method can fully compete with. Casting can enable complex designs cost efficiently and save costs by cutting the need for assembly work. Additionally, the material properties can be customized to meet application specific requirements. Three major casting methods are sand casting, investment casting and die casting (Campbell 2015). In this thesis, the sand casting method is in focus.

In sand casting an expendable mould is made of a mixture of sand and a binder. The mixture is packed on a pattern that has the shape of the desired casting as well as shapes for metal reservoirs and pouring channels, namely feeders and sprues. The moulding sand replicates the pattern and after hardening the pattern itself can be removed. The mould consists of two sides which, when assembled, have the complete pattern as a cavity inside the mould. This cavity is filled with molten metal that after solidification has the shape of the pattern. After opening the mould, the casting will be fettled and the feeders and sprues are removed. The casting is now ready for final heat or surface treatments where the final properties are achieved.

Sand casting manufacturing is rather energy and labour intensive. If the production series are short, as is the case of the foundries examined in this thesis, the vast majority of working steps are performed manually by the operators. The energy consumption depends on the properties of the casted material and is proportional to the total tonnage of castings and casting yield. This thesis seeks answers whether the use of modern exothermic feeders can give holistic economic benefits for foundries. There are multiple studies on the performance of different feeders (Oloke-Ehisuan 2019, Williams 2016, Purwadi, W., Idamayanti, D., Ruskandi, C., Kamal, J. 2016) but they do not cover the cost aspect. The few studies that concern sand casting cost formation (Chougule, Ravi 2006, Hundal 1993) are discussing the impact of feeding only superficially as the focus of these studies are the total cost formation.

This thesis is an empirical case study of two cast iron castings and one steel casting in two different foundries located in Finland. The study is limited to the following foundry processes: (1) mould preparation, (2) melt shop and casting, (3) blasting and (4) fettling and heat treatment and is focusing on the holistic economic benefits achieved with modern exothermic feeders. The modern exothermic feeders used in the case studies are ASK Chemical's KL mini risers. Among other comparable feeders from other manufacturers the KL mini risers are the only ones that can also be moulded manually. This is a significant advantage and a requirement of the foundries examined.

The economic benefits are calculated based on data gathered empirically and cost information from the foundries and raw-material suppliers. No overhead or design costs are considered, only the direct manufacturing costs related to the previously mentioned processes.

2 Characteristics of feeding in castings

In this chapter the general purpose and characteristics of feeding are described in order to give the reader a deeper insight in the function of feeding. Besides that, also the specific characteristics of feeding in steel and iron castings are presented.

2.1 General purpose of feeding

The main purpose of feeding is to compensate for the shrinkage of the casted material during casting. Without sufficient feeding the casting could have unwanted cavities or other defects related to insufficient material. (O. Yucel 2018, Keskinen, Niemi 2015) As the molten material is cooling down its volume is following a material specific volume-temperature curve which is dependent on the state of the material. (Svensson, Svensson 2020) As presented in Figure 1, the shrinkage can be divided into three different phases: (1) shrinkage in liquid phase, (2) shrinkage during solidification and (3) shrinkage in solid phase.

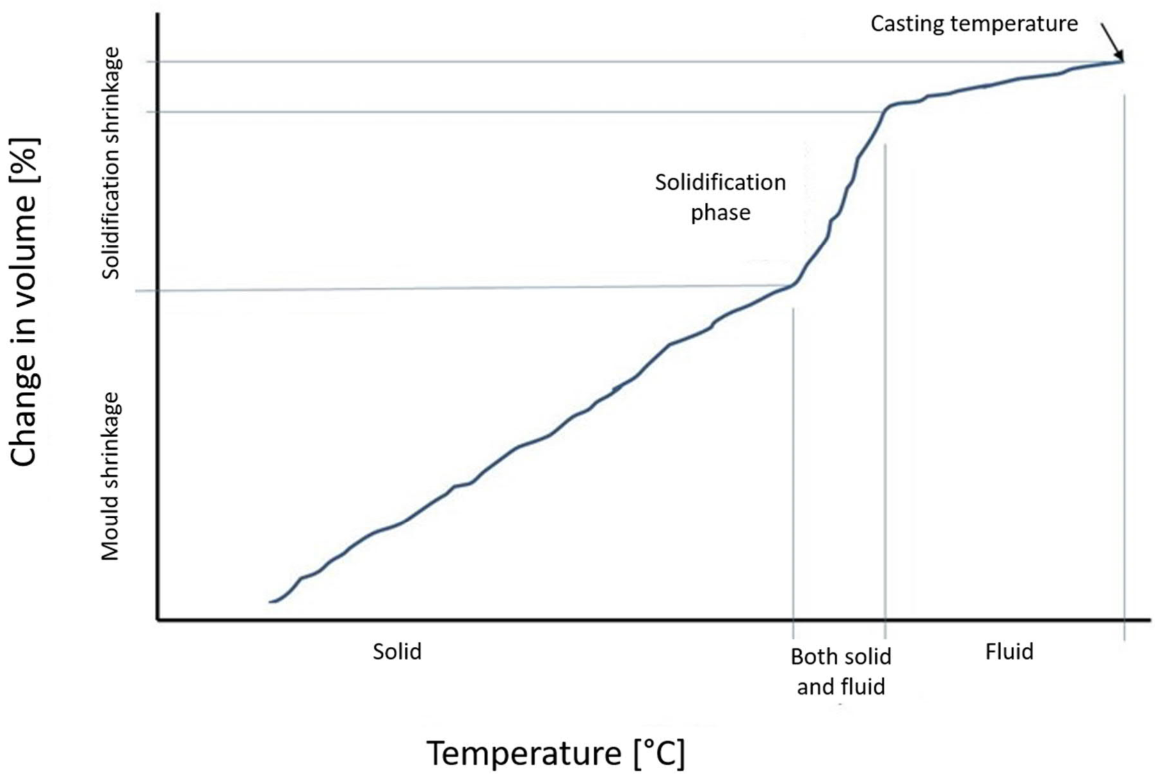

Figure 1. A generic volume-temperature curve showing shrinkage in different phases of cooling. (Svensson, Svensson 2020)

As Figure 1 implies, the shrinkage during these three phases can vary significantly. The shrinkage during fluid phase is rather constant at around 1,5% per 100°C for most of the materials. The shrinkage during solid phase, mould shrinkage, vary between 0.6-3.0% depending on the metal. (Svensson, Svensson 2020) However, the most relevant factor regarding feeding is the shrinkage during solidification. At this phase, the feeder(s) must feed the same amount of material as the material is shrinking in the mould.(Autere, Ingman et al. 1986)

2.2 The feeding system

The feeding system can consist of feeders, feeding paddings, chills and covering powders (Autere, Ingman et al. 1986). Feeders are the main reservoir for additional liquid material. The rest are used to improve the feeder's efficiency. Paddings are excess protrusions designed adjacent to the casting geometry to achieve the oriented solidification, for example an increasing wall thickness towards the feeder. Chills are metal blocks that are inserted in the mould with the function of cooling down the molten metal in specific areas. By this chilling effect it is possible to achieve oriented solidification without changing the part geometry. Chills can also be used to divide the casting into multiple feeding areas, thus decreasing the feeding distance for a single feeder. Covering powders are applied on top of open feeders to isolate the feeder metal from the surrounding air, thus prolonging the feeding time.

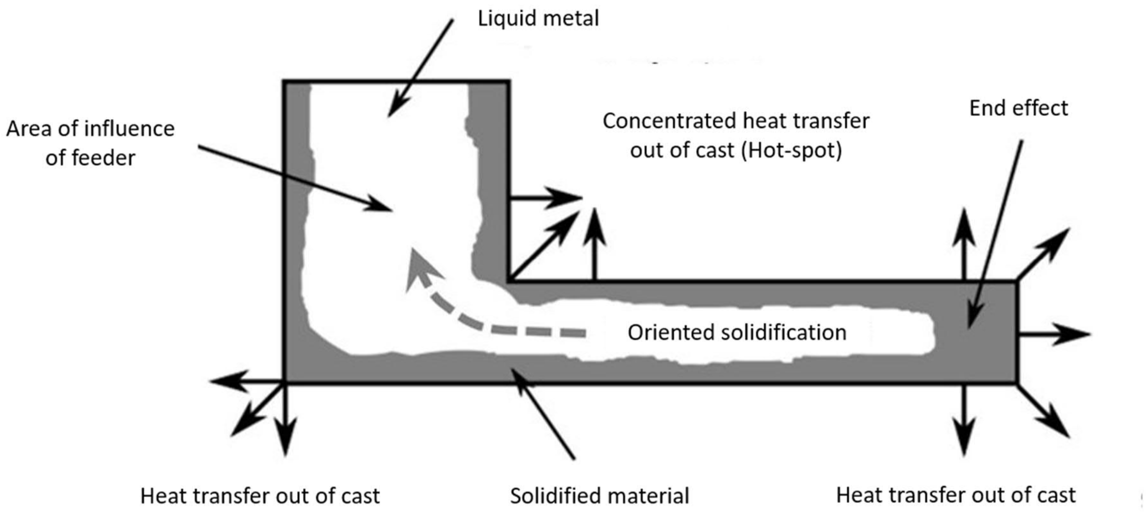

Figure 2 Oriented solidification towards the feeder. (Svensson, Svensson 2020)

Solidification of a casting starts from the area with the most heat dissipation. In Figure 2, this would be the rightmost end with all but one side facing the mould. The faster cooling of such a protrusion is called the end effect. The surrounding mould walls cool down the melt more than areas surrounded by hot molten material. Areas that cool down slower are called hot-spots and will solidify last. This is due to smaller heat dissipation area seen in Figure 2 in the elbow of the casting. The hot-spot is surrounded by molten material and heat is dissipated with a slower rate.

2.3 Feeding principles

When designing a feeding system, three conditions should be met (Autere, Ingman et al. 1986):

1. Feeding distance
2. Feeder modulus
3. Feeder volume

Firstly, the feeder should be able to feed material to the cast effectively enough so that no part of the cast is beyond the influence of the feeder. This means that there should be no closed isotherms inside the casting (Autere, Ingman et al. 1986). The feeder will not feed the whole casting if closed isotherms exist. The solidified sections of castings create barriers that isolate the feeders from the areas requiring feeding. If feeding is unsuccessful, the risk of cavities and other defects is increased.

The feeding distance depends greatly on the material, but also on the casting's geometry and the use of chills. The cross section of the fed area should be increasing towards the feeder. (Svensson, Svensson 2020) One way to calculate the required increase in the cross section is to draw spheres with an increasing diameter at the material specific distances of each other. The method and calculations for increasing spheres are presented in Figure 3.

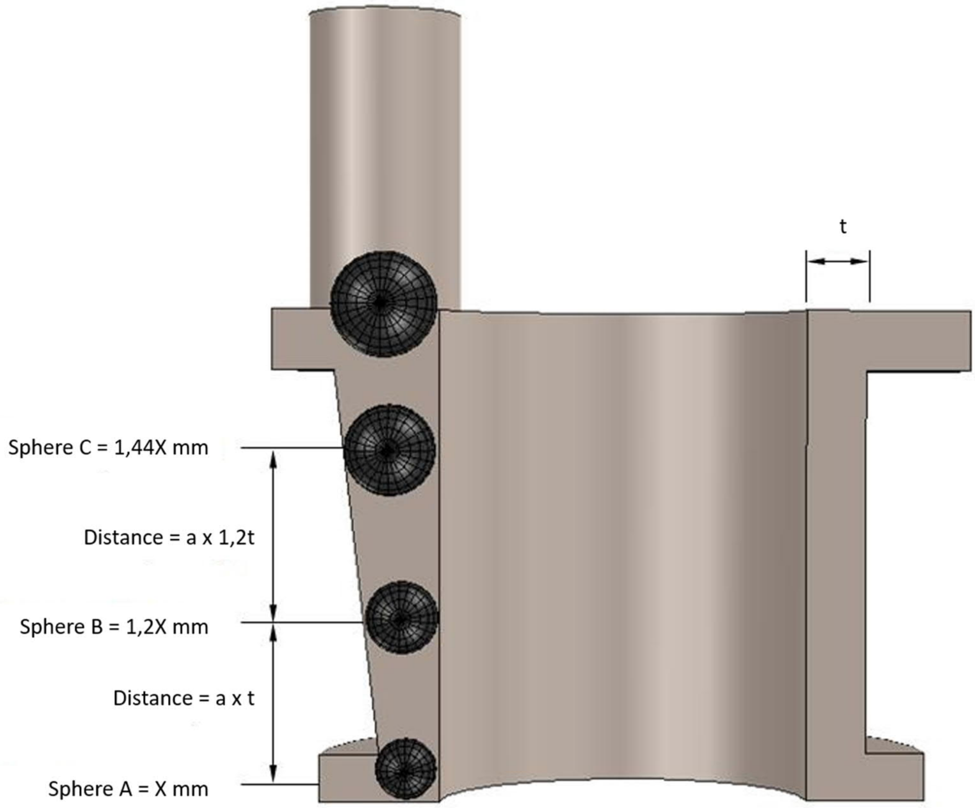

Figure 3. Illustration of calculation principle of increasing cross section towards the feeder. The spheres are increasing 20% in diameter for each feeding step. The feeding steps, *a*, are material specific and are calculated based on the wall thickness, *t*. (Svensson, Svensson 2020)

The same effect as with increasing the cross section is achieved by inserting chills into the areas that need to solidify first. Chills are inserted next to the casting wall in the mould during mould preparation. They have higher thermal conductivity than moulding sand and will increase the heat dissipation in the immediacy. This way solidifying can be set to start from the farthest areas without altering the casting's geometry.

Secondly, the feeder should have a sufficient modulus that is, for most materials, greater than the modulus of the casting. The modulus of the feeder is decreasing during solidification as the amount of material in the feeder is decreasing, hence the requirement for a higher modulus than the modulus of the casting. (Autere, Ingman et al. 1986) For some materials, such as grey cast iron, the optimum modulus for the feeder is smaller than the modulus for the casting (Svensson, Svensson 2020, Campbell 2015).

The modulus is the relation between volume and surface area, effectively telling about the heat capacity versus heat flow out of the casting. The equation (1) for calculating modulus is usually using centimetres as the unit. (Autere, Ingman et al. 1986, Svensson, Svensson 2020)

$$Modulus = \frac{volume\ cm^3}{cooling\ area\ cm^2} = M = \frac{V}{A} cm \qquad (1)$$

The modulus formula indicates that the most beneficial shape for a feeder would be a sphere, because then the relation between volume and area would be the greatest. However, cylindrical feeders are preferred in practice. Spheres would be more challenging to apply to the mould and would also generate closed isotherms in the feeder neck. The latter would efficiently hinder oriented solidification towards the feeder.

Thirdly, the volume of the feeder must be sufficient so that it can compensate for the whole shrinkage until solidification (Asthana, Kumar et al. 2006). The feeder yield should be considered when defining suitable feeder volume. The yield is heavily varying between different feeder types, which are described in detail in Chapter 3.

The practical feeder dimensioning is a compromise between performance and cost. Too narrow safety margins can cause defects and pose stricter requirements for process robustness. However, big feeders contribute to increased costs as cast yield is decreased. It is estimated that 37% of overall energy usage of foundries is wasted on cast yield losses (Schifo, Radia 2004). However, it must be noted that cast yield is also influenced by sprues and not only by the feeding system.

2.4 Differences in feeding of iron and steel castings

When casting cast iron or steel castings, a different approach for feeding properties is required. Properties that affect the feeding are for example flowability, shrinkage and chemical stability (Karjalainen 2020). Cast iron material shrinkage can be compensated by graphite expansion, thus decreasing the feeder volume and modulus (Karjalainen 2020). For iron the required feeder modulus is less than the casting modulus (Svensson, Svensson 2020). For steel, the feeder modulus should generally be 1.2 times the modulus of the casting (Autere, Ingman et al. 1986).

The flowability of steel is worse than the flowability of iron (Autere, Ingman et al. 1982). This can affect feeding distance by decreasing the distance how far a single feeder is able to feed. This depends mainly on the solidification range of steel, which is greater than with iron. In the solidification range barriers of partly solidified material are hindering free material flow and subsequently hindering feeder operation.

The chemical properties of the melt can also limit the suitable feeder types. The effects of inoculation of iron might be lost if the metal is molten for an extensive time or if the temperature is too high. This concern is mostly relevant when using exothermic aids in feeding. (Karjalainen 2020, Kurz, Fischer 1986)

3 Types of feeders

In this chapter, the different types of feeders and their characteristics are presented. Besides this, the different types of feeders are compared to give the reader an overview of how they perform in different applications.

3.1 Natural feeders

Natural feeders are created by shaping the sand in the sand mould so that a suitable shape for a feeder is created in the sand. Natural feeders are usually open, as seen in Figure 4. The shape and the position of feeders are restricted as the mould for creating the feeder must be removed before the mould can be assembled for use.

Benefit of having open-top feeders is that the gas that is created during casting can exit the casting and decreasing the risk of gas related problems (Karjalainen 2020). The disadvantages with open-top feeders in casting mould preparation are that they require multiple working steps as the feeder moulds must be removed. Due to the open top, the finish of the mould must be done with caution so that no excess sand or other material fall in the feeder. The cleaning of the mould must also be more thorough as it is anyway difficult to avoid sand accumulating inside the feeder.

During casting, feeders will fill up with molten material which will heat the surrounding sand. The relative modulus of the natural feeder is the lowest among different feeders as the sand will allow the most heat dissipation to the environment, thus cooling the feeder. This cooling rate is sand dependant and varies from foundry to foundry.

Figure 4. Natural feeders with open top.

3.2 Isolating feeders

Isolating feeders have an isolating hollow sleeve in the mould, as seen in Figure 6. Isolating sleeves are put in place during mould preparation and will stay in the mould during casting. As the feeder is staying in the mould it can also be made with a closed top unlike a natural feeder.

The benefit of isolating feeders is that the same modulus can be achieved with decreased volume. The sleeve acts as insulation between the melt and the sand and heat dissipation is decreased. Also, the risk of mould sand getting in the cast is reduced as the feeder sleeve is isolating the sand from the molten metal during mould preparation and casting.

Isolating feeders are made of fibre slurry which gives an airy texture to the sleeve. However, the mechanical strength is restricting the maximum wall thickness. This gives an upper limit on the increase in modulus. If the wall thickness is too great the sleeve can collapse of the hydraulic pressure of the molten metal and loose its' insulating properties.

Figure 5. Isolating feeder with breaker core that reduce the feeder neck size.

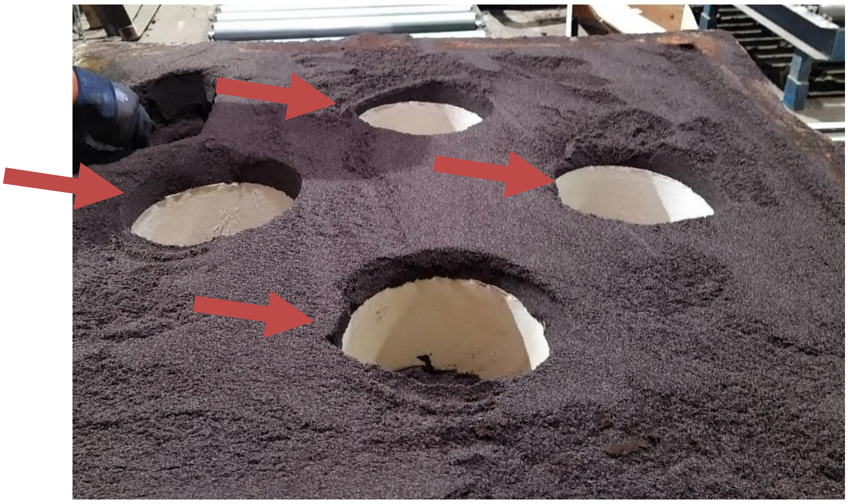

Figure 6. Isolating feeders with open top in a finished mould.

3.3 Conventional exothermic feeders

Exothermic feeders are from the application perspective the same as isolating feeders; the application of exothermic feeders is done during mould preparation, and they are left in the mould during casting. Some different shaped fibre based exothermic feeders are presented in Figure 7.

The main differences of exothermic feeders compared with isolating feeders are that exothermic feeders generate heat that will keep the feeder operating for a longer time. The generated heat will compensate for the dissipated heat through sand to the environment.

Figure 7. Fibre based exothermic feeders. (Intermet Refractories Limited 2020)

When molten metal is poured from the ladle to the mould, the feeder will first absorb heat from the metal. When the feeder reaches its ignition temperature the material in the feeder starts an exothermic reaction, for example the Goldschmidt Reaction (2). (Poole, Cox 2019, O. Yucel 2018)

$$2Al + Fe_2O_2 \rightarrow Al_2O_3 + 2Fe \qquad (2)$$

However, due to the reaction occurring in the feeder, which is in direct contact with the molten metal, there is a possibility of contamination or other unwanted interaction. This can lead to undesired changes in the material properties. (Poole, Cox 2019) The prolonged solidification time can also affect the material properties, for example the grain structure of cast iron (Kurz, Fischer 1986).

With exothermic feeders, it is possible to achieve higher relative modulus as the heat flow out of the feeder is starting only after the exothermic material is consumed and heat generation has ended. The same restrictions as for insulating feeders regarding wall thickness apply also on conventional exothermic feeders.

3.4 Modern exothermic feeders

Modern exothermic feeders differ significantly from conventional exothermic feeders. Firstly, the material of the feeder is a mix of sand and exothermic material, thus giving superior mechanical strength. The mechanical strength enables greater wall thicknesses, thus increasing the insulation and amount of exothermic material. Higher wall thicknesses have been identified as one beneficial factor for feeders when examining cast yield improvement (Wlodawer 1966).

Secondly, modern exothermic feeders differ in how they are applied in the mould. Conventional feeders, both insulating and exothermic, are set in their final position during mould preparation. The operator must then ram mould sand manually under the feeders during mould filling. Failure to ram sand properly around feeder neck exposes for cast defects.

Modern exothermic feeders are using guiding pins that (1) align feeders in correct position and (2) allow easier ramming of moulding sand under the feeder. The guiding pin will leave the feeder slightly elevated during mould preparation as in Figure 8. This will allow moulding sand to access the underside of the feeder. The operator will then press the feeder downwards and ram the sand with the feeder. This will replace manual ramming and give more even results. The guiding pin will, besides centring the feeder, position the feeder on a suitable distance from the mould cavity. Moreover, the guiding pin allows tilted installation of feeders, thus giving more freedom to designers. (ASK Chemicals GmbH 2015)

Figure 8. ASK KL mini riser feeders in elevated position before pouring of moulding sand.

Thirdly, the modern exothermic feeders are easy to remove in the fettling shop thanks to a metal collar that reduces the feeder neck size. Compared with conventional feeders' breaker cores, the metal collar gives a sharper breaking edge (Urreiztieta 2019). The metal collar can be seen in Figure 9, marked with green colour. The metal collar functions also as protection against sand during moulding. It will keep the sand out in both feeder positions and slide effortlessly inside the feeder during pressing down.

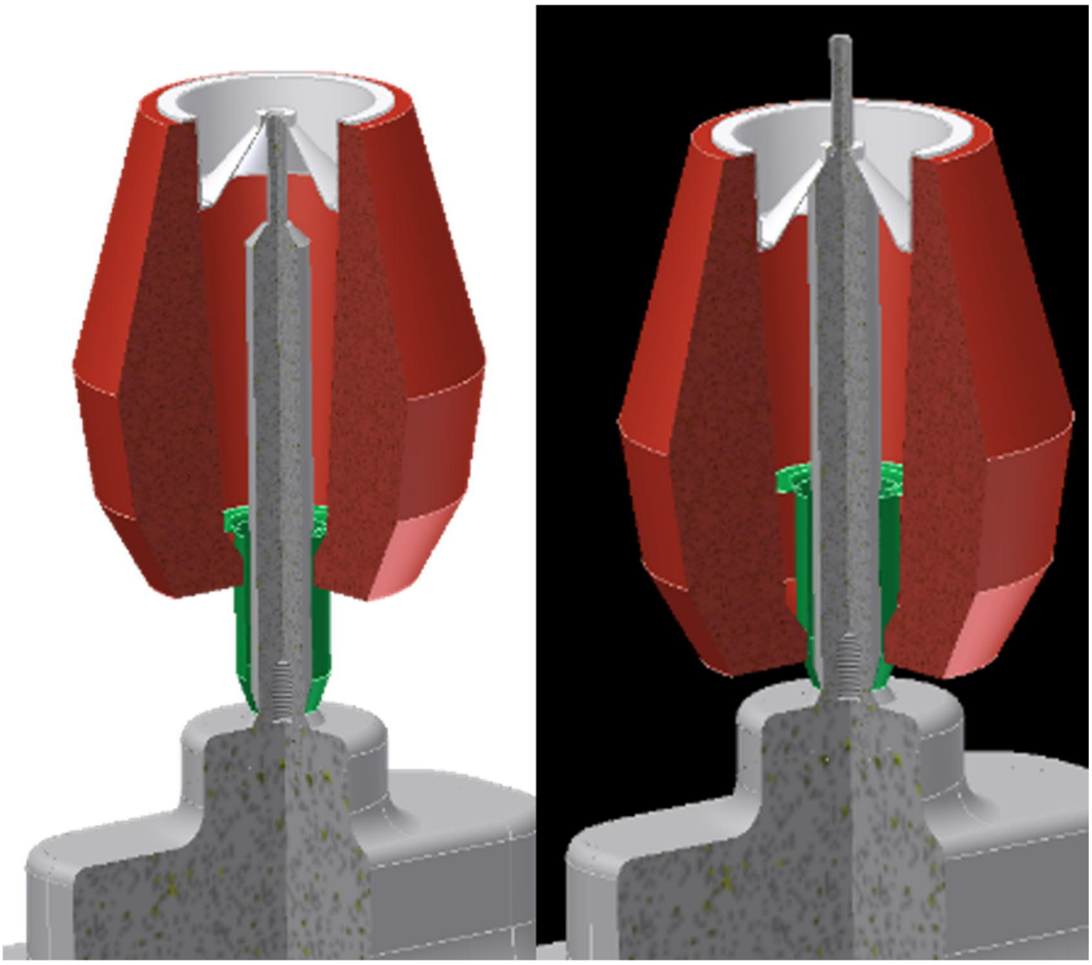

Figure 9. ASK KL mini riser in (1) elevated position after mould preparation and (2) in final position after pouring moulding sand and pressing the feeder down.

3.5 Externally heated feeders

Externally heated feeders are an alternative to exothermic feeders. The external heat is created with an electric current, either via induction (Poole, Cox 2019) or via diffusion (Seo 2018). The heat in inductively heated feeders is generated by passing an alternating current through an induction coil surrounding the feeder. The current in the coil induces currents in the metal inside the feeder. These currents heat the material due to the material's internal resistance (Poole, Cox 2019). With diffusion the surrounding of the feeder is heated with thermal elements that prevents heat flow out of the feeder and re-heats the material in the feeder.

Externally heated feeders can be re-used as there are no irreversible reactions as in exothermic feeders. However, they are more complicated to use than the other feeder types and are not yet used in a big scale. (Poole, Cox 2019) Externally heated feeders require a different type of infrastructure in foundries. Processes and workforce requirements are also different compared with other feeder types.

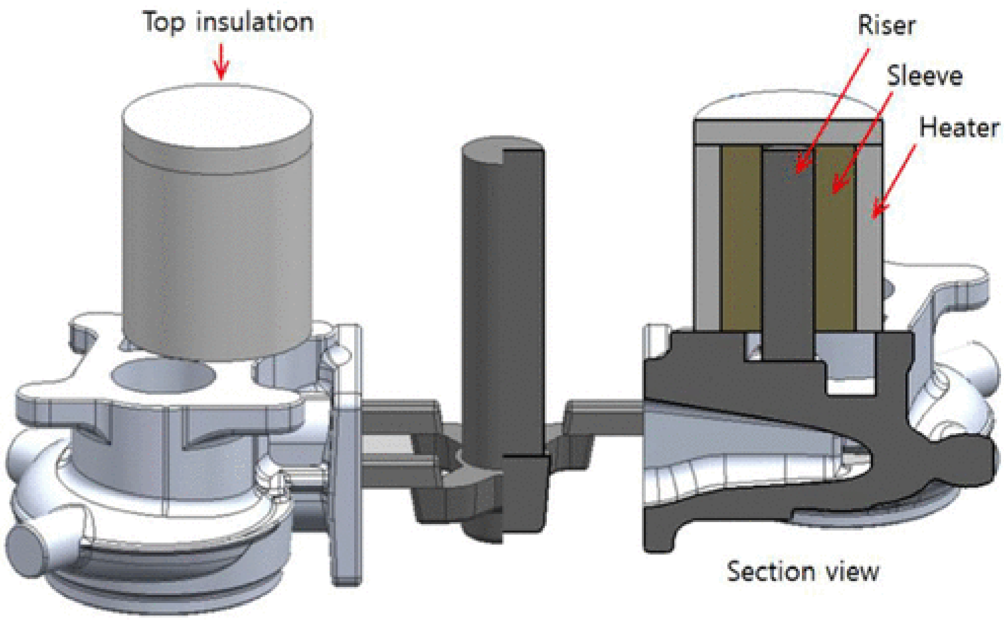

Figure 10. Example of an externally heated feeder with heating elements. (Seo 2018)

The externally heated feeders are not in direct contact with the melt, as seen from Figure 10. Thus, there is no physical interaction between the heating elements and the molten material. This is a benefit that externally heated feeders have compared with exothermic feeders' exothermic reaction that is occurring in direct contact with the melt.

3.6 Comparison of feeders

As stated in Chapter 2, feeding is highly affected by the material properties and the casting geometry. It is not possible to find universal truths regarding feeder performance only based on feeder characteristics. However, some generic values for feeder yield are presented in Table 1. The feeder yield is telling how big share of the feeders' volume the feeder can feed before solidifying.

Table 1. Comparison of feeder yields for different type of feeders.

Feeder type	Feeder yield	Source
Natural, open	10-15%	(Autere, Ingman et al. 1986, Svensson, Svensson 2020)
Isolating, covered	30-35%	(Autere, Ingman et al. 1986)
Exothermic, open	30%	(Svensson, Svensson 2020)
Exothermic, covered	50-70%	(Svensson, Svensson 2020)
Modern exothermic	70%	(ASK Chemicals GmbH 2015)
Externally heated, covered	60-70%	(Poole, Cox 2019)

4 Foundry processes and cost structure

In the beginning of this chapter, the general cost structure of a foundry is explained. This is followed by a presentation of the foundry processes of this study and their cost related parameters measured in the study.

4.1 General cost structure in foundries

The costs related to castings consist of material, energy, tool, labour and overhead costs (Chougule, Ravi 2006). The material costs can be divided into direct and indirect costs to clarify the difference between what the casting consists of and what material is needed to cast the casting. The detailed costs are presented Figure 11.

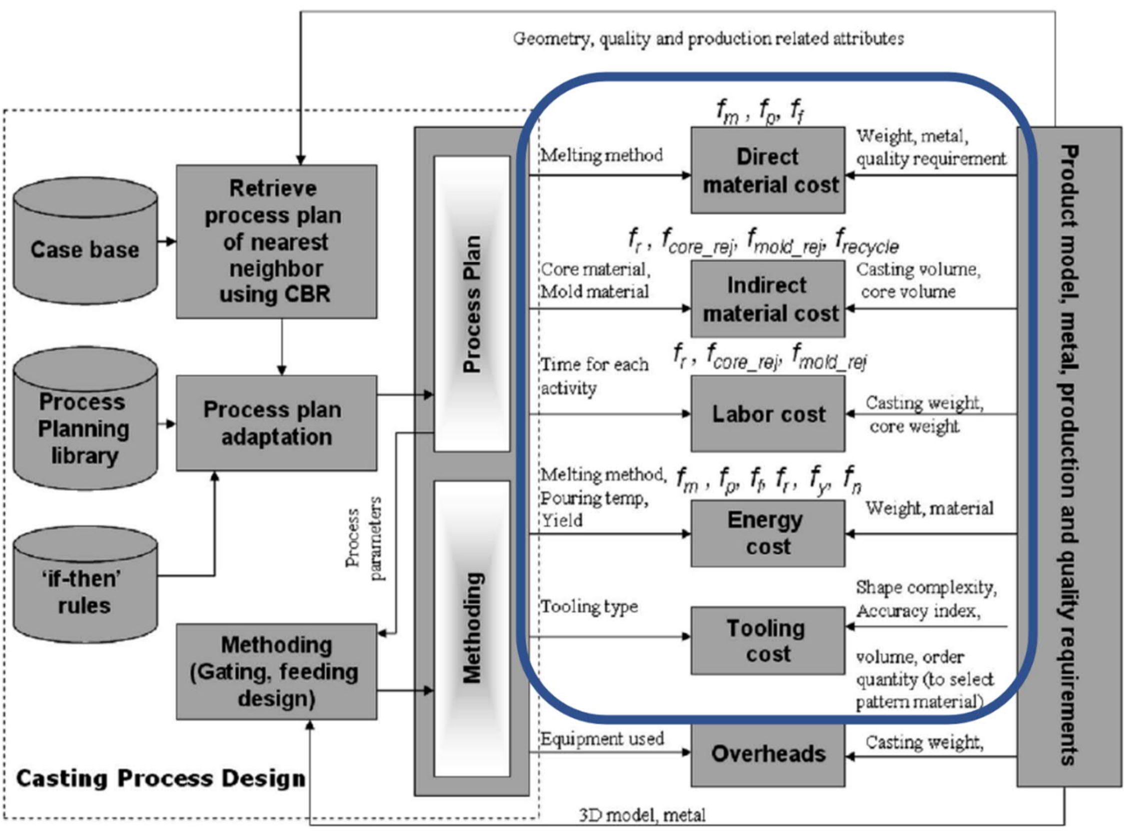

Figure 11. The process of cost estimation and the different parameters affecting cost formation of a casting. In this thesis, the costs inside the blue box that were affected by the feeder change are examined. (Chougule, Ravi 2006)

It is evident that the costs of foundries accumulate over several factors that can be linked to each other. The focus of this thesis lies in studying these linkages by replacing the feeders with modern exothermic ones and then observing how a limited selection of costs will be affected. By this limitation, the cost impact is clearer, and the results can be applied to a wider range of foundries. The costs and selected foundry processes are presented in the following sub-chapters.

4.2 Mould preparation

Mould preparation includes the working steps to make an assembled mould ready for casting. The process starts with pairing the pattern with a suitable sized mould frame. The following step is to insert the sprue and the feeding system on the pattern. After this, the moulding sand is poured and compacted inside the mould frame. The final step is to extract the pattern and coat the surfaces that are in contact with the molten metal. The examined costs in this process are related to materials and labour and are as following:

1. Time used for top mould half preparation
    - Starting from the point where the pattern and the mould frame are already assembled
    - Ending to the point where the mould was set to wait before the extraction of the pattern
2. Cost of raw materials
    - Cost of feeders

The mould preparation labour could be affected by the change of feeder type and the material cost of feeders is most likely changing. Changes in other material costs, such as sand consumption, are not relevant as they are either negligible or not affected by the feeder type. The bottom half of the mould is also not affected by the feeder type.

4.3 Melt shop and casting

In the melt shop, the casted metal is melt and treated to achieve the desirable material characteristics. When the melt is ready, it can be poured to the mould. The mould is then left to rest during the metal solidification and cooling. The examined costs in this process are related to materials and energy and are as following:

1. Cast yield
    - The volume of the final casting compared with the entire casting with feeding and filling systems
2. Cost of melting metal
    - Direct energy costs related to melting material

The cast yield is most likely affected by the feeder change. As material amounts are changed, the energy costs will differ. The raw-material costs are not relevant to consider as the net weight of the castings is not changing and excessive material is returned to the melt shop.

4.4 Blasting

Before blasting, the casting has been removed from the mould. In blasting, it is shot blasted to clean the surface of sand and other residue accumulated during casting. The costs in this process are related to materials and are as following:

1. Cost of steel grit exiting the process
    - Amount of steel grit exiting the shrunken feeders.

With large diameter feeders, large amounts of steel grit can exit the process. With the feeder change, the feeder geometry and size will be changed and, thus, the amount of grit conveyed away from the blasting chamber may change.

4.5 Fettling and heat treatment

After shot blasting, the feeders, sprues and eventual feeding paddings will be removed. The common tools used in fettling includes sledgehammers, different grinders, air cannons, flame cutting machines to name a few. The extent of fettling varies from casting to casting, but in the castings examined the fettling was a preliminary stage before machining. The costs in this process are related mainly to labour but also to tooling and are as following:

1. Total time used
    - Starting from the point where the casting was set on the fettling workstation
    - Ending to the point where the casting was ready to be removed from the fettling workstation
2. Need of heat treatments due to thermal stress during fettling
    - If feeders can be removed with methods that do not stress the castings thermally, thus eliminate the need for heat treatments
3. Tool wear
    - Direct tool costs due to wear

As the feeding system is altered, the amount of labour in fettling is most likely changed. This could impact on the need for heat treatments, depending on the working methods used to remove feeders. Furthermore, if the geometry of the feeding system is different, it is possible that the direct tool costs, such as consumption of cutting discs, might be changed. Indirect tool costs are not considered, as it is most likely that the tools are used in other castings and would anyway be invested in.

5 Castings

In this chapter the three different castings studied in this thesis are presented.

5.1 Casting 1: roller

Casting number 1 is a cast iron roller with an approximate net weight of 280 kg. Casting 1 is presented in Figure 12. The part is symmetrical with four symmetrically placed feeders. The feeders are located on the edge of one of the rollers' sides. The roller is cast in an upright position. The feeders are so called top feeders as they are located highest in the mould. The feeders are replaced with ASK Optima KL 430 mini risers.

The feeding distance of each feeder is rather long. Therefore, both feeding paddings and chills are used. The chills help to gain oriented solidification towards the feeders and separate the feeders to their own feeding areas. The feeding padding is added for two reasons; (1) to move the thermal focus closer to the feeder and (2) to make room for the feeder neck whose diameter is greater than the one of the edge where the feeder is located.

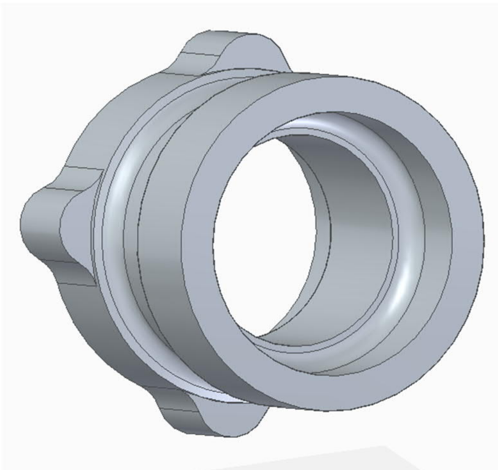

Figure 12. Casting 1, roller, with feeding paddings. The final part is without the protrusions on the back half of the part.

5.2 Casting 2: machine base

Casting number 2 is a cast iron machine base with an approximate net weight of 300 kg. Casting 2 is presented in Figure 13. The feeding system of casting 2 consists of three insulating open-top feeders of two different sizes. The feeders are located highest in the mould. Thus, they are so called top feeders. The feeders are replaced with two ASK Optima KL 430 mini-risers and one ASK Optima KL 237 mini riser.

The material soundness requirements are strict in certain specific areas and, therefore, feeding is focused on these locations. Chills were used at the bottom of the mould to let the farthest areas from the feeder to solidify first. No feeding paddings were used in this part.

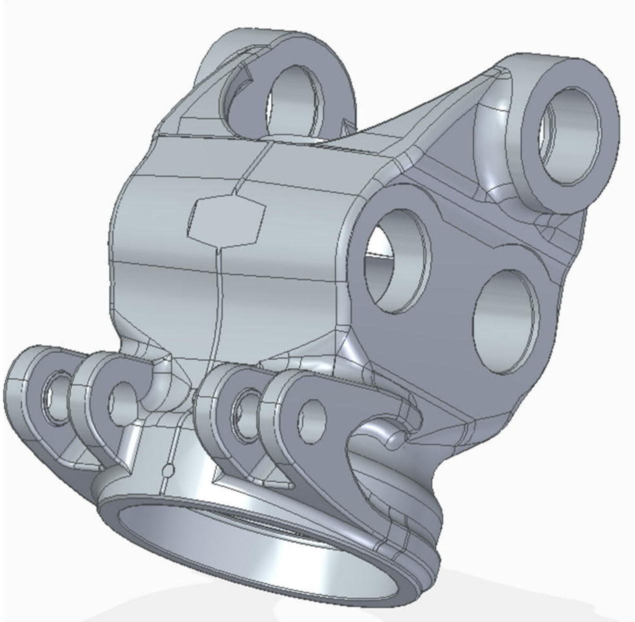

Figure 13. Cast 2, machine base.

5.3 Casting 3 pump cover

Casting number 3 is a steel pump cover with an approximate net weight of 50 kg. Casting 3 is presented in Figure 14. The part is fed with multiple closed exothermic feeders on both the inner and outer rim. The feeding of the cover is demanding as the part is widespan but rather small volume wise. To gain oriented solidification, the feeders must be relatively close to each other as the isotherms are parallel on both the outer and inner rim unless close to a feeder. The feeders are replaced with Optima KL 237 mini risers.

Figure 14. Casting 3, pump cover.

6 Results: Economic benefits with modern exothermic feeders

In this chapter the results of the case studies are presented. Firstly, the individual findings per each process are presented for all the three castings. Secondly, a cost impact is calculated.

6.1 Differences in mould preparation

Differences in mould preparation between isolating and modern exothermic feeders are clearly visible for casting 1 and 2. A caption during moulding of insulating feeders for casting 1 is presented in Figure 15. Pouring of sand has been suspended while the isolating feeders and their top covers are set in place. For casting 1, the moulding of feeders can be divided into three phases: (1) pouring of moulding sand at the level of feeder necks, (2) shaping moulding sand around the feeder base and the insertion of feeders and (3) filling up the rest of the mould frame. The feeders cannot be set in place beforehand as the feeders' relatively large diameter is preventing the sand entering the underside of the feeder. Additionally, even if sand would enter, it is difficult to pack properly around the feeder neck.

Figure 15. Casting 1 upper mould half during moulding with isolating feeders. The view has been taken during installation of feeders before the rest of the moulding sand is poured.

With modern exothermic feeders, the sand mixer can run continuously. The feeders can be set in place during mould preparation and only needs to be pressed down after their base has been surrounded by sand. This working phase is seen in Figure 16. This totals in one single working step related to feeder moulding and two working steps overall. There is no need to move the sand by hand as the relatively small feeder diameter will let the sand to flow in sufficient amounts under the feeder. The pressing down will compact the sand evenly around the feeder neck as seen in Figure 17. The pressing down will also be less operator dependant as the guiding pin will limit the movement and all the operator checks are binary. The feeder is either up or down and the sand is either poured on all sides or not. Less subjective measures make the process easier to master.

Figure 16. Casting 1 with modern exothermic feeders during pressing down. The sand mixer could run continuously.

Figure 17. Modern exothermic feeder from inside the mould after pattern removal of casting 2. The metal ring visible around the hole is the feeder's metal collar that keeps the moulding sand out of the feeder and creates a sharp breaking edge in the near proximity of the casting.

The findings discussed above apply for casting 2 as well. The process and current feeding system of casting 2 was built up using the same principles, so the differences should be minor. However, both the diameter and the number of feeders in casting 2 were smaller. The operator was, for example, able to install the isolating feeders without interrupting the sand mixer. As long as the feeders were prepared as presented in Figure 18, the benefit of not stopping the mixer was not actual.

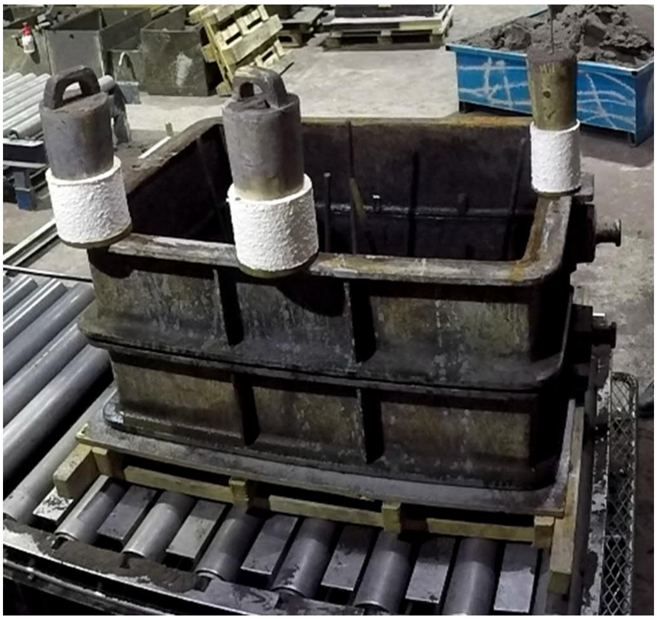

Figure 18. Casting 2 prior to sand pouring with feeders prepared for installation.

Overall, the number of working steps related to feeders were significantly higher in casting 1 and 2 with the isolating feeders than with the modern exothermic feeders. The process steps with insulating open-top feeders were (1) sand shaping, (2) feeder insertion, (3) feeder cover insertion, (4) feeder cover removal and (5) feeder cleaning. Feeder cover removal is presented in Figure 19 and the reason for feeder cleaning is seen in Figure 20. The process steps for casting 2 are identical, except the feeders and covers are assembled beforehand (see Figure 18), as the moulding can then be performed without stopping the sand mixer in between. Only step 2 is required with modern exothermic feeders, thus simplifying the process significantly.

Figure 19. When evening out the surface of the mould, the feeder covers must be removed individually to minimize the amount of moulding sand falling in the feeder.

Figure 20. Insulating feeder in casting 1 with moulding sand inside the feeder that must be removed manually.

Casting 3 was moulded with closed feeders from the beginning. Thus, the difference in labour time and working steps were not significant after the feeder change. The exothermic feeders did not need compacted sand beneath the feeder as the exothermic feeder's breaker core was resting directly against the pattern. The feeders could be put in place during mould preparation which eliminated the need to install feeders simultaneously with the sand mixer running. The mould filling process seen in Figure 21 is straightforward regardless of feeder type. However, some level of packing of sand is required to fill the areas directly next to the feeders. This imposes a risk of lifting the feeder from its position if the sand is packed wrongly. A small benefit with modern exothermic feeders was the structure consisting of a single part compared with the two-part exothermic feeder (see Figure 22).

Figure 21. Casting 3 moulding where the sand pouring includes an extra working step compared with the conventional exothermic feeders.

Figure 22. Casting 3 current exothermic feeder type without cap (left) and after cap installation (right).

The overall results of differences in mould preparation process generated by using modern exothermic feeders are summarized in Table 2 and in greater detail in Appendix 1. The time of mould manufacturing was measured from the moment when the assembled mould frame and pattern started moving from the mould preparation line. At this point, the mould frame, sprues and eventual chills were already in place. The clock was stopped when the mould was evened out and was rolled out to wait for pattern removal. The additional savings and benefits listed in Table 2 are based on the author's observations and the operators' remarks. The results on casting 3 with modern exothermic feeders rely on one sample as the production que and risk of part failure did not allow a bigger sample.

Table 2. Impacts in mould preparation when using modern exothermic feeders.

	Casting 1		**Casting 2**		**Casting 3**	
	n = 2	n = 2	n = 2	n = 2	n = 2	n = 1
	Old	New	Old	New	Old	New
Difference in working time		-20%		-29%		-2%
Feeder cost difference		+47%		+72%		+88%
Additional savings and benefits with modern exothermic feeders	Less components to be stored in mould shop. Less working steps and possibilities for human errors. Simpler process, easier to train for new operators. No sand inside feeders. 23 kg less scrap sand due to one less mixer start-up.		Less components to be stored in mould shop. Less working steps and possibilities for human errors. Simpler process, easier to train for new operators. No sand inside feeders.		Less components to be stored in mould shop.	

6.2 Differences in melt shop

The size differences for the feeders were considerably big for castings 1 and 2. The current isolating and the modern exothermic feeders used in casting 1 are presented in Figure 23 and Figure 24. The current feeders were a mix of isolating and natural feeders because the moulding frame came higher than the isolating feeder's sleeve during moulding. As the mould was filled with moulding sand to the level of the frame, the height of the feeder was increased. If the whole volume would had been a natural feeder, the module would have been circa 3.6 cm but the isolating feeder will increase the module to circa 4 cm. In either case, the modulus to volume ratio is significantly larger for the modern exothermic feeder, as stated in Chapter 3.

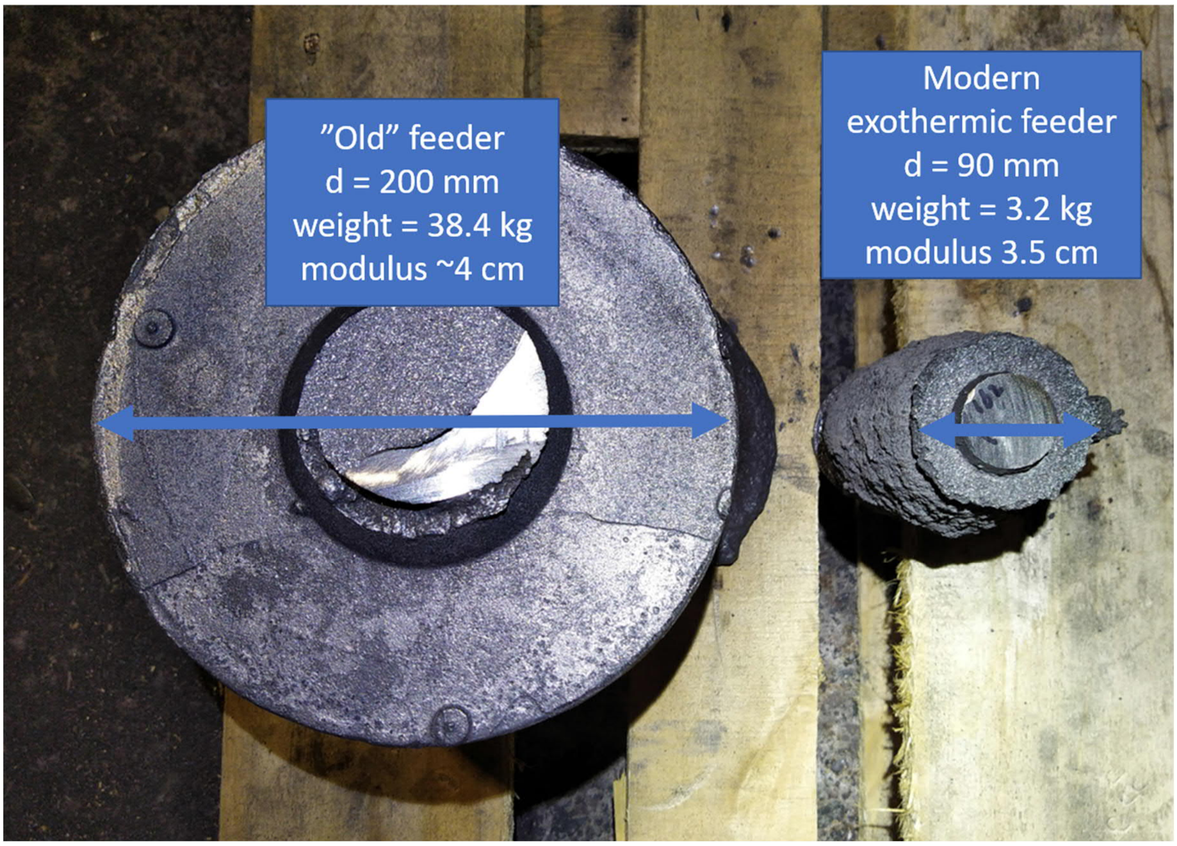

Figure 23. Casting 1 feeder comparison. The isolating feeder (left) is significantly wider and heavier than the modern exothermic feeder (right). The modern exothermic feeder with a comparable modulus is over ten times smaller.

For casting 1 the weight difference per feeder was 35.2 kg totalling in material savings of 140.8 kg as the casting had four feeders. The gross weight of the casting with current feeders was around 480 kg and the cast yield consequently 58%. With the modern exothermic feeders, the cast yield was increased to 83% as the gross weight was decreased to circa 340 kg. The total weight reduction with modern exothermic feeders was 29%. With such savings it would be possible to cast one extra roller after 2.4 casts. The theoretical energy savings were €25.40 per casting.

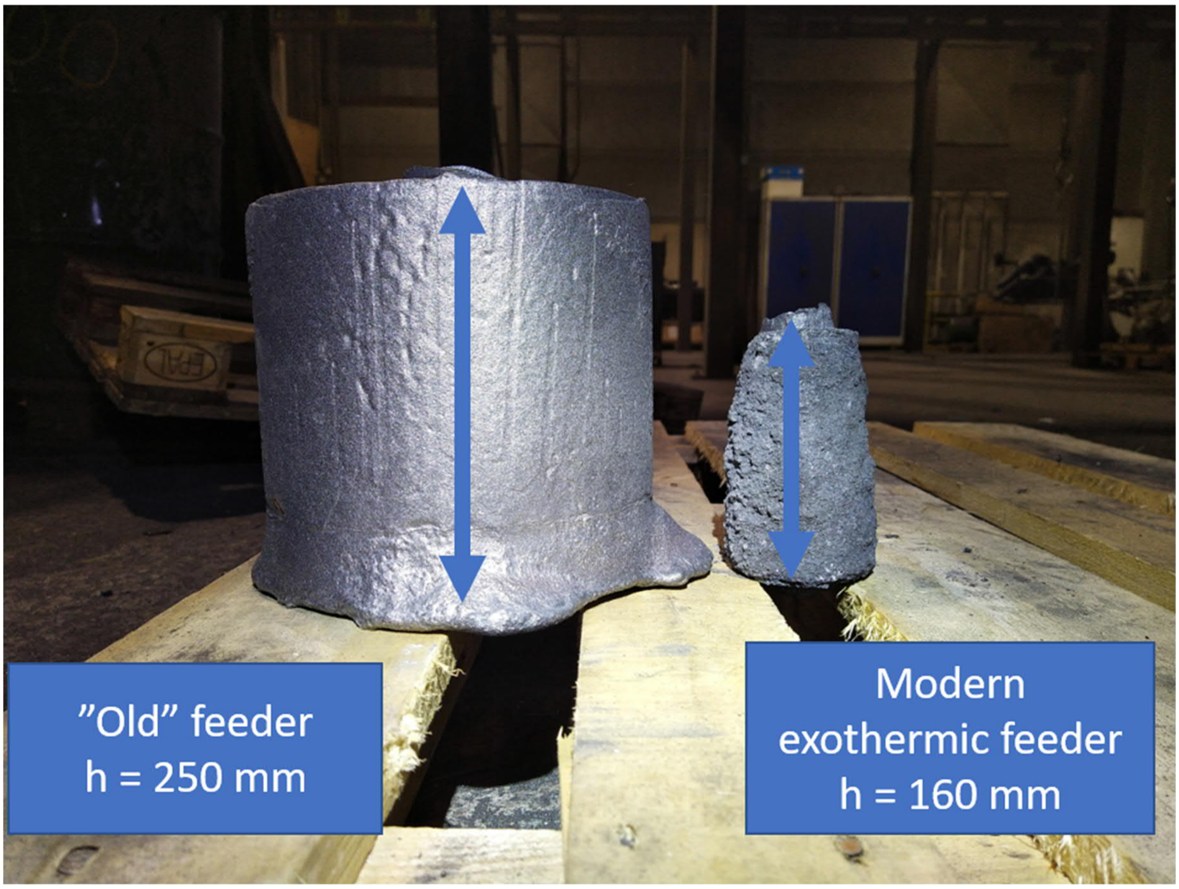

Figure 24. Casting 1 feeder height comparison. The isolating feeder (left) is not itself that much higher than the modern exothermic (right), but as the isolating feeder is an open top it will get the height of the moulding frame.

The results for casting 2 are following the same path as the results for casting 1. However, as there were only three feeders, the differences are slightly smaller. The overall weight reduction was 19% and the cast yield changed from 67% to 83%. The material savings would accumulate so that materials for an extra cast would be saved every 4.2 casts. The theoretical energy savings were €15.60 per casting.

Casting 3 was already using conventional exothermic feeders. Therefore, the weight between the two types of feeders were almost identical. The modern exothermic feeder used in casting 3 was 0.4 kg heavier than the current conventional exothermic adding 2% to the casting's gross weight. The characteristics of both feeders are presented in Figure 25 which reveal that the modulus of the modern exothermic feeder is 0.1 cm higher and could explain the bigger mass. The theoretical energy consumption was increased by €0.42 per casting when using modern exothermic feeders.

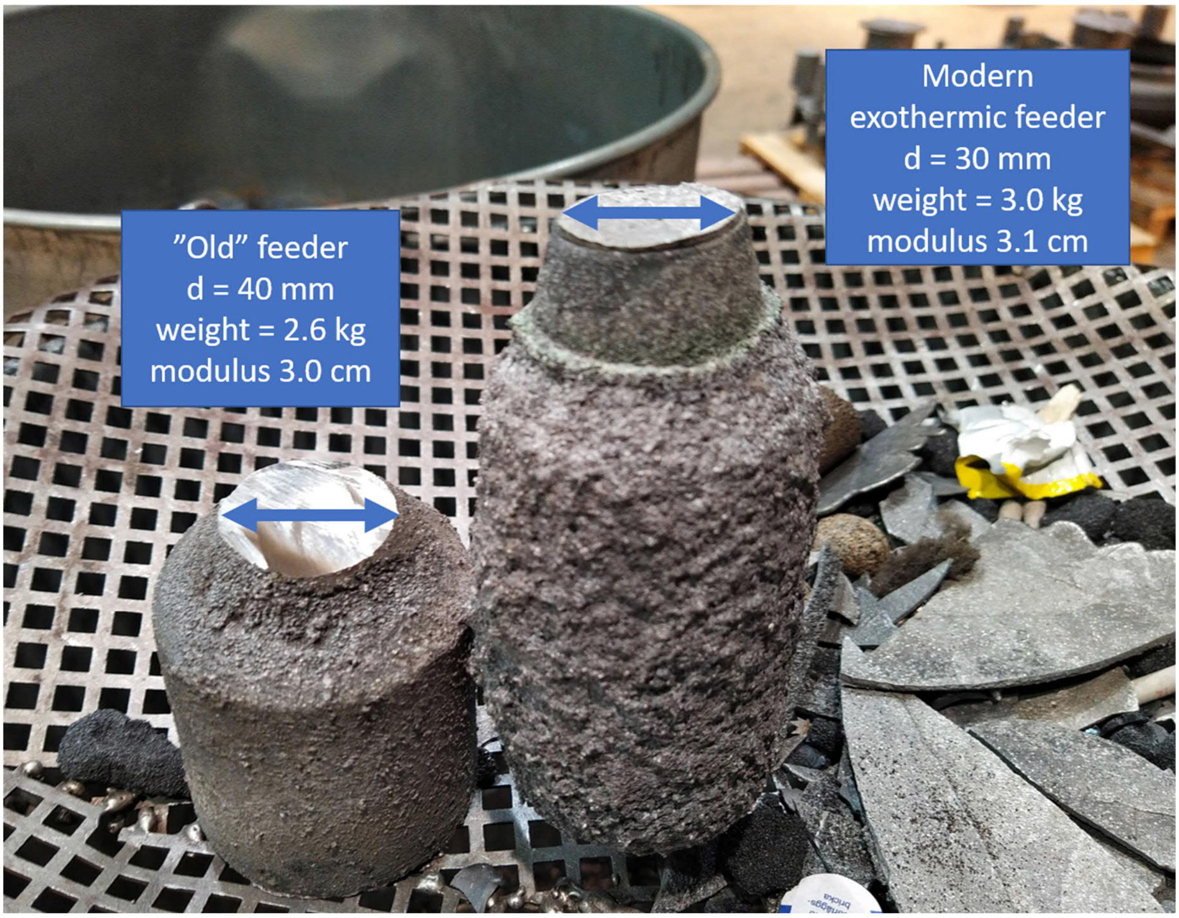

Figure 25. Casting 3 feeder comparison. The current exothermic (left) with a slightly smaller weight than the modern exothermic feeder (right).

The results discussed above are summarized in Table 3 and presented in deeper detail in Appendix 2. Regarding casting 1 the second sample with modern exothermic feeders was failed during casting for reasons not related to the feeders. Therefore, the sample was decreased to one.

Table 3. Impacts of modern exothermic feeders in melt shop.

	Casting 1		**Casting 2**		**Casting 3**	
	n = 2	n = 1	n = 2	n = 2	n = 2	n = 1
	Old	New	Old	New	Old	New
Casting gross weight	480 kg	340 kg	450 kg	364 kg	96 kg	98 kg
Feeding system weight	153.7 kg	12.7 kg	95.6 kg	9.0 kg	21.2 kg	23.6 kg
Cast yield	58%	83%	67%	83%	55%	54%
Weight/Energy cost change		-29%		-19%		+2%
Number of castings to gain one extra		2.4		4.2		-41.2

6.3 Differences in blasting

The factual feeding of different feeders varied significantly between different castings, but also between the same castings. In Figure 26, one of the four feeders of casting 1 sample 1 is presented. The surface is rather even and allows no suitable niches for steel grit to accumulate, especially if compared with casting 1 sample 2 seen in Figure 27.

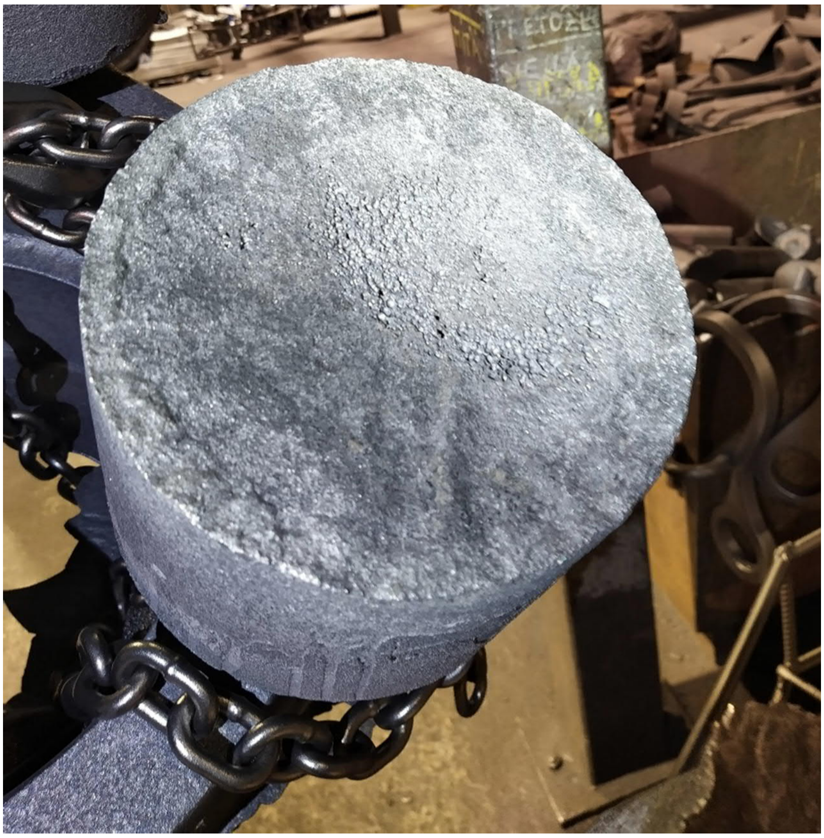

Figure 26. Casting 1 sample 1 feeder. The feeder has either not been feeding that much or has stayed molten long enough to even out the top surface

The feeders of casting 1 sample 2 have been sinking more and would provide pockets for steel grit to exit. However, as seen from Figure 27 the feeder is fully cleaned from steel grit by the blast chamber operator and no steel grit was exiting.

Figure 27. Casting 1 sample 2. The isolating feeder has fed the casting after the walls of the feeder have been solidified, thus creating a cavity in the molten centre of the feeder.

The feeders of casting 2 generally had more sinks on top of the feeder than casting 1. One of the three feeders of casting 2 is presented in Figure 28. Even though there would be a cavity suitable for steel grit to get trapped, the mode of working in foundry A took care of the problem and the change to modern exothermic feeders did not change the amount of steel grit exiting the process.

Figure 28. Casting 2 isolating feeder with excessive sink.

Even though no measurable differences were found between the different feeders, the modern exothermic feeders were easier to clean as there were fewer open cavities. The modern exothermic feeder for casting 1 is presented in Figure 29 which shows that the upwards shaped cone without sinks does not need any effort from the operator to be grit-free.

Figure 29. Casting 1 modern exothermic feeder that is easier to clean as the diameter is smaller and the conical shape does not collect steel grit.

The method of working in foundry B was different and the eventual cavities on the feeders could trap some steel grit that was transported away from the blast chamber. However, the amounts were extremely small as can be seen in Figure 30. Overall, the economic benefits achieved with the examined castings were negligible and are not affecting the holistic economic impact of modern exothermic feeders.

Figure 30. Casting 3 current exothermic feeders collect some steel grit in the recess located on the top of the feeder created by the feeder lid.

6.4 Differences in fettling and heat treatment

The small feeder neck diameter was the most beneficial feature of the modern exothermic feeders in fettling for all the case castings. The feeder necks for casting 1 are compared in Figure 31 and a significant difference can be seen. The insulating feeder with the wide neck was removed with an air cannon from both casting 1 and 2 directly after blasting before the actual fettling shop. The cannon in an operating position can be seen in Figure 32 just seconds before the impact, which will break the feeder neck and eject the feeder on the floor. Normally, the feeders should have been first cut to start with an angle grinder, but this was not performed. The relatively high stub seen in Figure 31 was left to be removed later.

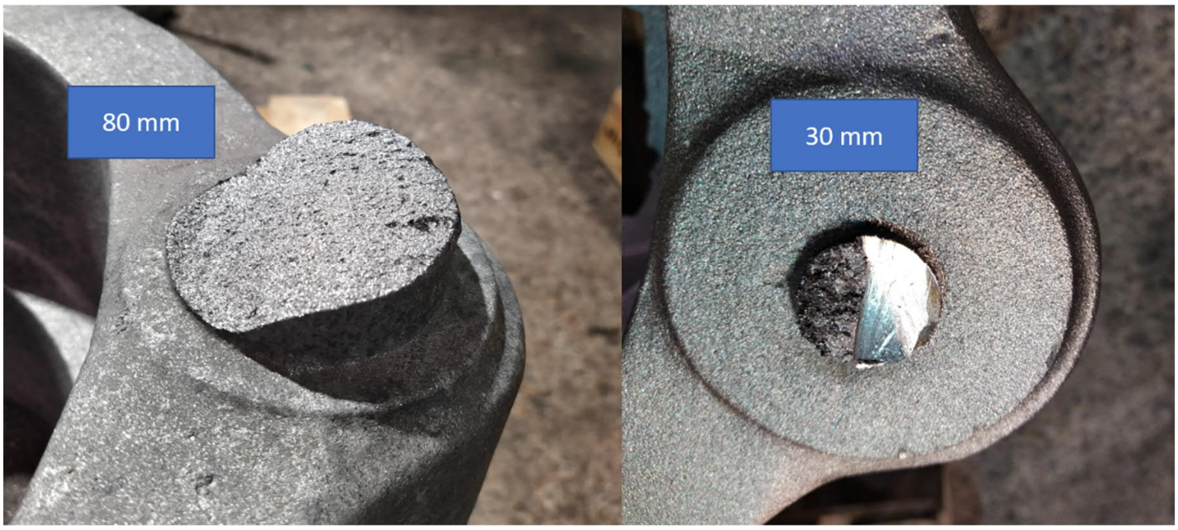

Figure 31. Casting 1 feeder neck comparison after feeder removal. The isolating feeder with breaker core (left) and the modern exothermic feeder (right).

The cannon is so heavy that it must be manoeuvred by crane and the operator must swing it towards the feeder before triggering the impact to decrease the recoil. The process of impacting the feeders was quick, but to pick up the cannon and to return it to the storage hook increased the total feeder removal time. Additionally, the pneumatic hoses were scattered on the floor where the operators were walking adding a risk of tripping.

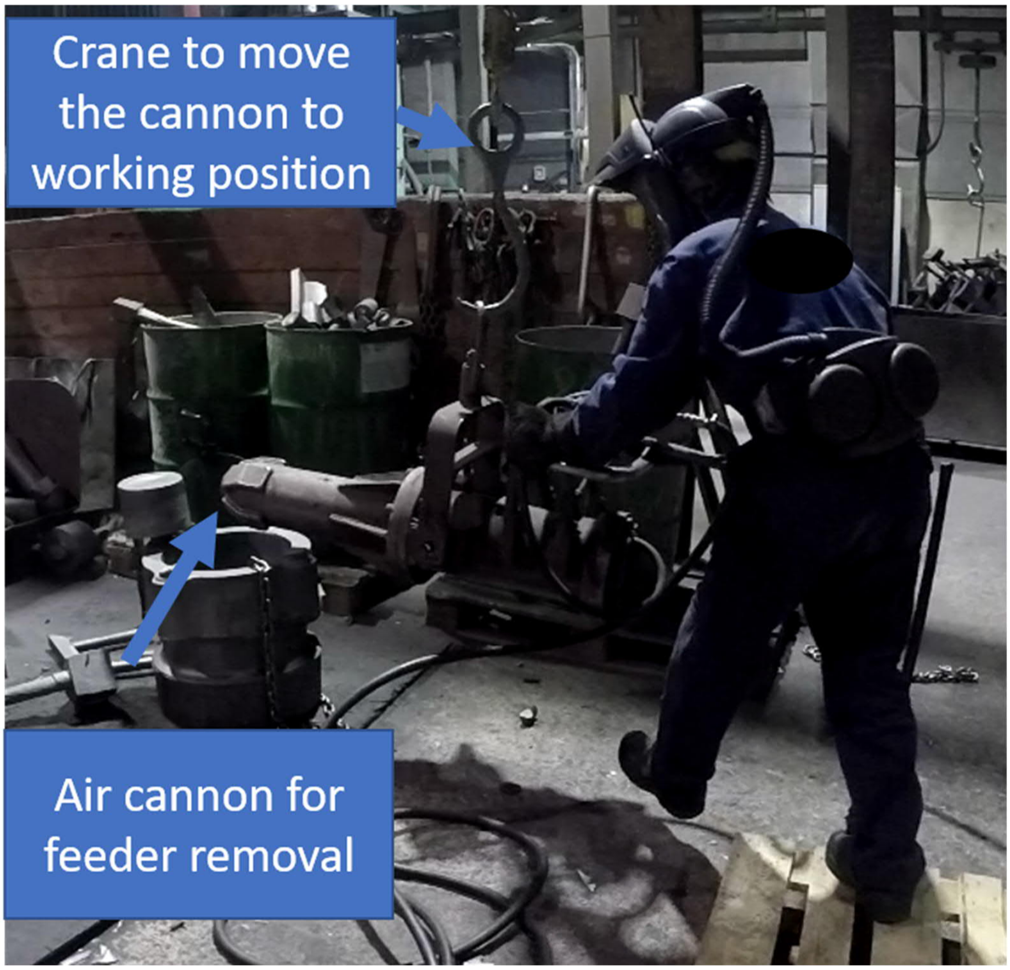

Figure 32. Crane operated air cannon for feeder removal in foundry A.

Modern exothermic feeders had a smaller diameter neck and a sharp cutting edge. Thus, the feeders could be removed simply with a light impact with a sledgehammer. As a result, the labour and tool costs were smaller. Additionally, the occupational safety was improved as the feeders were not literally flying around as they did when removed with the air cannon.

After the feeders were dismantled from the casting, they were sorted into bins that later went for re-melting. The isolating feeders in casting 1 were ranging from 33.6 to 43.40 kg and for casting 2 from 18.8 to 43.4 kg. Thus, the correct method was to move them by crane as seen in Figure 33. However, the operator for the first sample of casting 1 threw them manually. The time for lifting the four feeders of sample 2 to the sorting bins by crane was 3 minutes, which was added to the feeder removing time for the first sample of casting 1 to give results that reflects the by-the-book operations.

The modern exothermic feeders ranged from 3.05 to 3.25 kg for casting 1 and from 2.3 to 3.55 kg for casting 2. The low weight enabled moving the dismantled feeders by hand, thus making the process faster. This would also decrease the risk of injuries related to lifting heavy feeders against the work instructions. The overall time from the start of feeder removal to the point when the feeders were lifted to the sorting bins for isolating feeders were decreased by 78% and 77% for casting 1 and 2 respectively.

Figure 33. Lifting of the feeders that have been ejected to the floor by the air cannon.

As the feeder necks of isolating feeders were quite high, they were first cut of in the fettling shop with an angle grinder with a cutting disk. Only after that, they could be grinded to the surface required by the machining. The cutting and grinding discs used for castings 1 and 2 during feeder stub removal were not wearing significantly, but especially in casting 1 the wide neck combined to the part geometry required a relatively fresh disc to reach to cut through the whole neck. This caused an unnecessary change of otherwise functional discs.

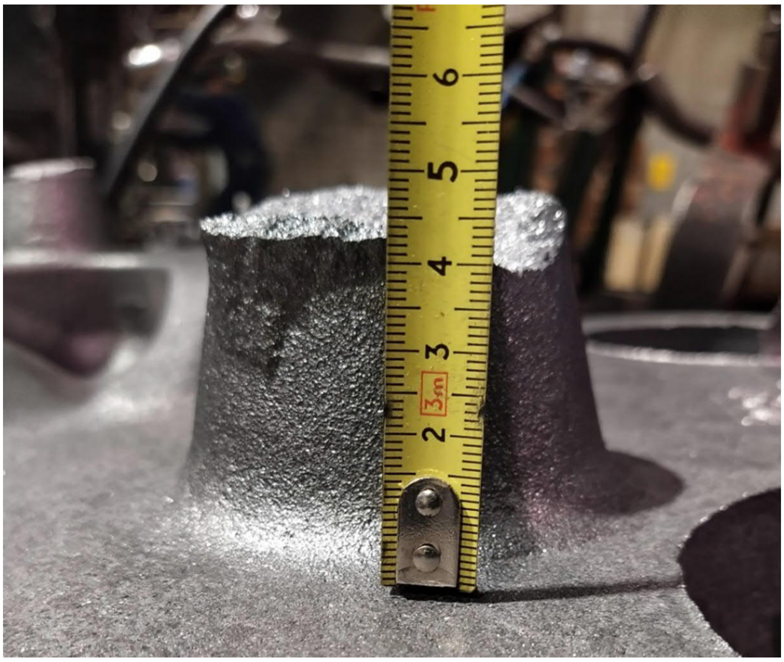

Figure 34. Casting 2 isolating feeder neck after feeder removal. The stub must be cut off before finalized by grinding.

The necks of the modern exothermic feeders of castings 1 and 2 did not require any cutting after feeder removal and so they were only grinded. The reason for no cutting can be seen from Figure 35, the stub is quite low with a small diameter is appropriate to grind. The feeder stub processing time of castings 1 and 2 was therefore be reduced significantly. For casting 1 with modern exothermic feeders the time was reduced by 74% and for casting 2 by 77%.

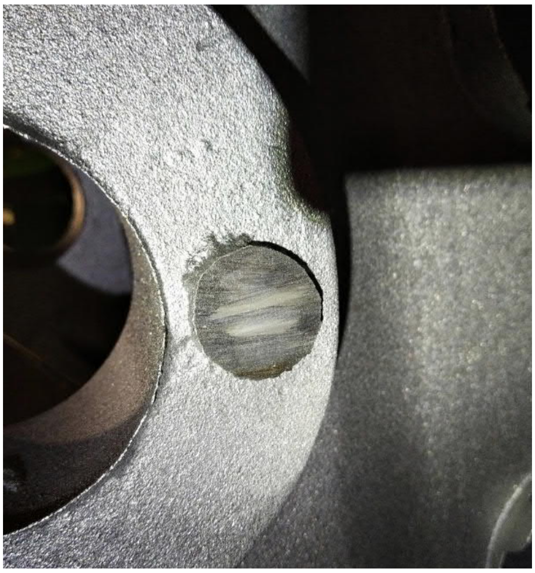

Figure 35. Casting 2 modern exothermic feeder neck with a diameter of 30 mm after feeder removal. The stub can be removed by grinding.

The removal of the current feeders for casting 3 took quite a long time as they were removed without knocking. The operator was using only an angle grinder. Therefore, the material had to be cut fully trough. Casting 3 had 6 feeders and so the differences in feeder removal times were clearly visible. The modern exothermic feeders could be removed without an angle grinder using only a one-hand hammer. The main reason for this is the sharp cutting edge seen in Figure 36 that will protect the casting so that the feeder cannot tear excess material from the casting itself, even without pre-cutting with an angle grinder. The feeder removal time for casting 3 was decreased by 89% and the feeder grinding time by 48%.

Figure 36. Casting 3 modern exothermic feeder neck with a sharp cutting edge.

When studying the impact of modern exothermic feeders on the whole fettling process the removal of sprues, flashes and eventual paddings were not affected by the modern exothermic feeders. However, to better understand the overall benefits in fettling, the whole fettling time was measured. The overall decrease of labour time for castings 1, 2 and 3 was 11%, 18% and 61% respectively. The measured working steps included the time from the part being lifted to the working station to the point where the fettling was done, and the castings were ready to be moved to machining. The results are summarized in Table 4 and more in detail in Appendix 3. None of the studied parts required heat treatments caused of thermal stress during fettling.

Table 4. Impacts to fettling when using modern exothermic feeders.

	Casting 1		**Casting 2**		**Casting 3**	
	n = 2	n = 1	n = 2	n = 2	n = 2	n = 1
	Old	New	Old	New	Old	New
Total time used (min.sec)	50.51	45.05	28.33	23.29	6.22	2.29
-feeder removal	4.42	1.01	3.13	0.45	2.59	0.20
-change		-78%		-77%		-89%
-feeder neck grinding	4.03	1.02	4.24	0.58	0.27	0.14
- change		-74%		-77%		-48%
Relative difference in total time		-11%		-18%		-61%
Remarks	Easier handling of feeders after dismantling due to weight decrease Smaller neck diameter needing less manual tooling Lighter tools needed to do the same work as before Less risk for the riser to come off with excess material from the casting without pre-cutting due to sharp breaking edge		Easier handling of feeders after dismantling due to weight decrease Smaller neck diameter needing less manual tooling Lighter tools needed to do the same work as before Less risk for the riser to come off with excess material from the casting without pre-cutting due to sharp breaking edge		Faster feeder removal due to sharper breaking edge	

7 Conclusions

The results discussed in the previous chapter are used here to calculate the holistic economic impact on the examined foundry processes. The results are presented in Table 5 as relative cost changes in each process when counting for the parameters described earlier in this thesis. The weight of the different processes varied from casting to casting, thus a high relative cost change for a single process is not necessarily contributing to a high absolute saving. The total weighted cost change is calculated by comparing the sum of the measured costs to the sum of cost change.

It can be concluded that when replacing isolating feeders with modern exothermic feeders it is possible to achieve significant savings. The savings are proportional to the number of feeders so that castings with more feeders generate higher savings. The total savings are 14% for casting 1 and 11% for casting 2. The major part of savings is achieved from the energy cost of melting metal but also the time of feeder removal is contributing to the overall savings. Especially for casting 1 the absolute savings for fettling are significant but the relative savings are rather modest due to long overall fettling time regardless of feeder type. The expected feeder cost increase of modern exothermic feeders was adding costs to mould preparation, especially with smaller feeder sizes.

When replacing conventional exothermic feeders with modern exothermic feeders, the savings were not realized with the examined casting. The overall costs increased by 31% due to higher feeder costs even though fettling of the casting was almost eliminated. With casting 3 the increased feeder costs affected mould preparation costs more than with other castings as the amount of labour was constant regardless of feeder type.

Table 5. Holistic economic impact of the use of modern exothermic feeders in the studied castings. The values for each process are the savings inside that process. The total cost change is calculated based on weighted savings.

Relative cost change per process	Casting 1	Casting 2	Casting 3
-mould preparation	+38%	+47%	+76%
-melt shop	-29%	-19%	+2%
-fettling and heat treatment	-6%	-18%	-89%
Total weighted cost change	**-14%**	**-11%**	**+31%**

Beyond the calculated results, it can be notified that multiple benefits, which are difficult to evaluate, could be achieved when using the modern exothermic feeders. The moulding process would be simpler with fewer steps, thus enhancing the quality and making it easier for new employees to internalize. The resources to cast bigger castings when the cast yield is increased was not evident with the studied castings but could be a deal breaker in suitable circumstances. The decreased weight of the feeders can benefit via smaller machine and tool investments and improved occupational safety. Additionally, the feeder size and freedom regarding its placement provides new possibilities for designers to cast complicated parts.

The sample size for this study was rather small due to limitations in the production series. This reduces the reliability of the results but as the differences were relatively large the results are reliable to determine whether the costs were increasing or decreasing. Also, as most of the processes were filmed it was possible to confirm afterwards if something exceptionally was affecting the process times, for example discussion breaks or operator mistakes. Such exceptions were corrected in the calculations so that the results reflect smooth operation.

The results are very casting specific and, therefore, no absolute values for cost savings can be generalized for other castings. However, with the results presented above, it is possible to reflect how different factors affect the eventual savings, thus giving valuable information to be used for other castings and other foundries. Each foundry should also have knowledge about their cost formation so that the results of this thesis can be reflected against their relevant costs.

8 Further research

The modern exothermic feeders provide more possibilities for designers when designing the feeding system. None of the potential was taken advantage in the castings of this study as it would have required major changes to the current patterns and casting design that would have fallen outside the scope of this thesis. To obtain full cost saving potential the customer, casting designer, pattern manufacturer and machining shop should all have to be included (Honkavaara 2017). However, the results obtained here give courage to continue with the improvements as it is already confirmed that the modern exothermic feeders can replace the existing ones without cast defects.

Regarding casting 1, the small size of the feeder itself and the small neck size could make it possible to remove or to decrease the size of the paddings seen in Figure 37. The modern exothermic feeder will fit on the edge of the casting contrary to the isolating feeder. The paddings were removed manually in the fettling shop and accounted for two-thirds of the whole fettling time. The tool costs were also significant as cutting discs had to be changed often. If the paddings are required to achieve a sufficient feeding distance, the paddings could also be made of an exothermic feeding padding that achieves the same result without excess metal that has to be removed.

Figure 37. Feeding paddings on casting 1 during removal in fettling shop.

All the inspected castings were simple regarding the feeder locations but still the feeder removal was significantly faster with modern exothermic feeders. In more complicated geometries, the feeders might be located surrounded by the casting, thus restricting the possible tools for removal. Such casts could benefit much more from the "knock-with-a-hand-hammer" type of feeder dismantling. In castings where feeders might be removed with flame cutting the savings could increase significantly if unnecessary heat treatments can be eliminated. Also, the longer the feeder removal time is in the beginning, the bigger savings could be achieved with modern exothermic feeders.

9 References

ASTHANA, R., KUMAR, A. and DAHOTRE, N.B., 2006. *Materials processing and manufacturing science.* Burlington, Elsevier. ISBN 075-067-716-3

AUTERE, E., INGMAN, Y. and TENNILÄ, P., 1986. *Valimotekniikka. 2.* Helsinki, Insinööritieto. ISBN 951-795-140-X

AUTERE, E., INGMAN, Y. and TENNILÄ, P., 1982. *Valimotekniikka. 1.* Helsinki, Insinööritieto. ISBN 951-793-538-2

CAMPBELL, J., 2015. *Complete casting handbook : metal casting processes, metallurgy, techniques and design.* Second edition. Amsterdam, Butterworth-Heinemann.

CHOUGULE, R.G. and RAVI, B., 2006. *Casting cost estimation in an integrated product and process design environment*. International Journal of Computer Integrated Manufacturing, 19(7), pp. 676-688.

ASK CHEMICALS GMBH, 2015. *ASK Training risers.*

HONKAVAARA, T., 2017. *Valutuotteiden valmistuslähtöinen suunnittelu tuotesuunnittelijan näkökulmasta*, Master's Thesis. Aalto University, Department of Engineering design and Production. Espoo. 74 p.

HUNDAL, M.S., 1993*Rules and models for low-cost design*, American Society of Mechanical Engineers, Design Engineering Division (Publication) DE 1993, pp. 75-84.

INTERMET REFRACTORIES LIMITED, 2020-last update, Bimex 369. Available: https://www.intermet.co.uk/bimex-369/ [15.7., 2020].

KARJALAINEN, H., 2020. Master of Science (Tech), Oy Lux Ab. Lars Sonckin kaari 16, 02600 Espoo. Interview 12.3.2020.

KESKINEN, R. and NIEMI, P., 2015-last update, *Valuatlas - 19. Muotin täyttöjärjestelmä.* Available: valuatlas.fi [24.6., 2020].

KURZ, W. and FISCHER, D., 1986. *Fundamentals of Solidification.* Aedermannsdorf, Trans Tech Publications Ltd.

O. YUCEL, 2018. *Effects of Changing Size-Weight Parameters on the Temperature Dependent Exothermic Riser Sleeve Properties.* Eurasian Chemico-Technological Journal , **20**(1), pp. 17-21.

OLOKE-EHISUAN, Y., 2019. *Effects of Inductive Heating on Risers in Casting Processes*. Master's Thesis. University of South Alabama, Department of Mechanical Engineering. Alabama. 82 p.

POOLE, G. and COX, M., 2019. *Influence of Coil Configuration and Operating Conditions on Heat Transfer in Inductively Heated Risers*. JOM, 71(1), pp. 40-47.

PURWADI, W., IDAMAYANTI, D., RUSKANDI, C., KAMAL, J., 2016. *Effect of shape variation on feeding efficiency for local exothermic-insulating sleeve.* AIP Conference Proceedings, 1778(1), . doi:10.1063/1.4965751

SANTACECILIA, P., 1992. *Increasing Manufacturing Competitiveness Through Information Technology: A Case Study*. Production and Inventory Management Journal, 33(2), pp. 80.

SCHIFO, J.F. and RADIA, J.T., 2004-last update, *Theoretical/Best Practice Energy Use In Metalcasting Operations*. Available: https://www.energy.gov/sites/prod/files/2013/11/f4/energyuseinselectedmetalcasting_5_28_04.pdf [1.7., 2020].

SCHMIDT, M., 2013. *Material Flow Cost Accounting as an Approach to Improve Resource Efficiency in Manufacturing Companies.* Resources, 2(3), pp. 358-369.

SEO, H., 2018. *Design of a gate system and riser optimization for turbine housing and the experimentation and simulation of a sand casting process.* Advances in Mechanical Engineering, 10(8).

SVENSSON, I. and SVENSSON, I., 2020. *Gjuterihandboken.* Jönköping, Gjuterininformationen i Jönköping AB. ISBN 91-631-6158-3

URREIZTIETA, J., 2019. *Latest developments on design and formulations of minirisers for the feeding of ductile iron and steel castings improving risers removal and yield with the consequent decrease on cost.* ASK Chemicals Feeding System s GmbH.

WILLIAMS, T., 2016. *Determination of effective riser sleeve thermophysical properties for simulation and analysis of riser sleeve performance*, Master's Thesis, University of Iowa, Department of Mechanical Engineering. Iowa.82 p.

WLODAWER, R., 1966. *Directional Solidification of Steel Castings.* New York, Pergamon Press Inc. ISBN 148-311-669-7

Appendix 1 Detailed results for casting 1

Appendix 2 Detailed results for casting 2

Appendix 3 Detailed results for casting 3